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A NOVEL 20 KW SOLAR SIMULATOR DESIGNED FOR AIR POLLUTION RESEARCH

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ABSTRACT

An atmospheric chamber facility for the study of photochemical air pollution at ambient pollutant concentrations has been established at the Statewide Air Pollution Research Center of the University of California, Riverside.* The facility consists of two environmental chambers and a 20 KW solar simulator. This paper describes the properties and detailed performance characteristics of the solar simulator, including beam intensity, spectrum, uniformity and collimation. The simulator was designed to the special requirements of the SAPRC facility, and subsequently built and tested by the Aerospace Controls Corporation.

I. INTRODUCTION

Investigations of the photochemistry of polluted atmospheres have been conducted in a variety of "smog chambers" in various laboratories in the United States during the past 20 years. The great majority of these chambers utilized UV blacklamps, or other conventional lighting systems, as a source of photolysing radiation. Studies conducted in such chambers have been criticized with regard to the lack of authenticity of both the spectral distribution and the intensity of radiation employed relative to that found in the troposphere.[1]

Thus, a major design consideration in establishing a new environmental chamber facility was to improve the quality of simulation of solar radiation with respect to previous studies. To this end the technology developed for aerospace solar simulation has been applied to the design and construction of a specialized solar simulator to be used specifically to investigate photochemical reactions in simulated, as well as ambient polluted urban atmospheres, and in simulated polluted stratospheric air masses. This goal necessarily imposed conditions and requirements different than those usually encountered in aerospace

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522-137 O - 73 - 53

applications of solar simulation. We here describe in detail the design and performance characteristics of the resulting 20 KW system which is currently in operation at the Statewide Air Pollution Research Center (SAPRC) of the University of California at Riverside, California.

II. BASIC CONSIDERATIONS IN THE SYSTEM DESIGN

The SAPRC laboratory houses two smog chambers, both having an approximate volume of 200 cubic feet. One chamber is of conventional "box-like" design with Pyrex walls supported by a metal frame. The second chamber is an evacuable, thermostatted, cylindrical vessel with an inside diameter of 52 inches and a length of 156 inches. Arrays of 16 fused silica panes (13 inches on a side) form the end windows of the evacuable chamber. The SAPRC solar simulator was designed for use primarily with the cylindrical evacuable chamber but it can also be employed with the glass chamber.

The dimensions of the evacuable chamber and the nature of the photochemical air pollution research to be conducted imposed constraints on several properties of the solar simulator beam. For example, it was deemed important to minimize irradiation of the walls of the chamber (constituting 84% of the total surface area) so as to reduce the contribution of light-initiated heterogeneous reactions to the gas-phase photochemistry being investigated. Since at the same time a minimum dark volume was desired, a high degree of beam collimation and a small solar subtense angle were dictated. In addition, at least one solar constant irradiance level in the photochemically important region from 250 - 500 nanometers, as measured by chemical actinometry in the chamber volume (and not just in the area of the cross section of the simulator beam), was a third stringent design requirement. An adjunct to this objective was that good spectral match to the solar spectrum be obtained in the actinic region defined above. Finally, although reasonable beam uniformity and stability were required, the long irradiation times involved in the research (5 - 10 hours) permitted less stringent requirements to be placed on these characteristics than is the case for most aerospace applications.

III. OPTICAL DESIGN

A diagram of the simulator optical design is shown in Figure 1. The M.E.C.[C] (Maximum Efficiency Contour) collector collects and projects the lamp output, via a 45° flat, onto the optical integrator. The integrator, in turn, projects the beam onto the spherical secondary mirror of a modified Gregorian collimating system with a parabolic primary. The surface of the secondary mirror contains the plane of superposition of the integrator channels. This uniform plane is imaged at the test plane (162 inches from the secondary) via the parabolic colli-

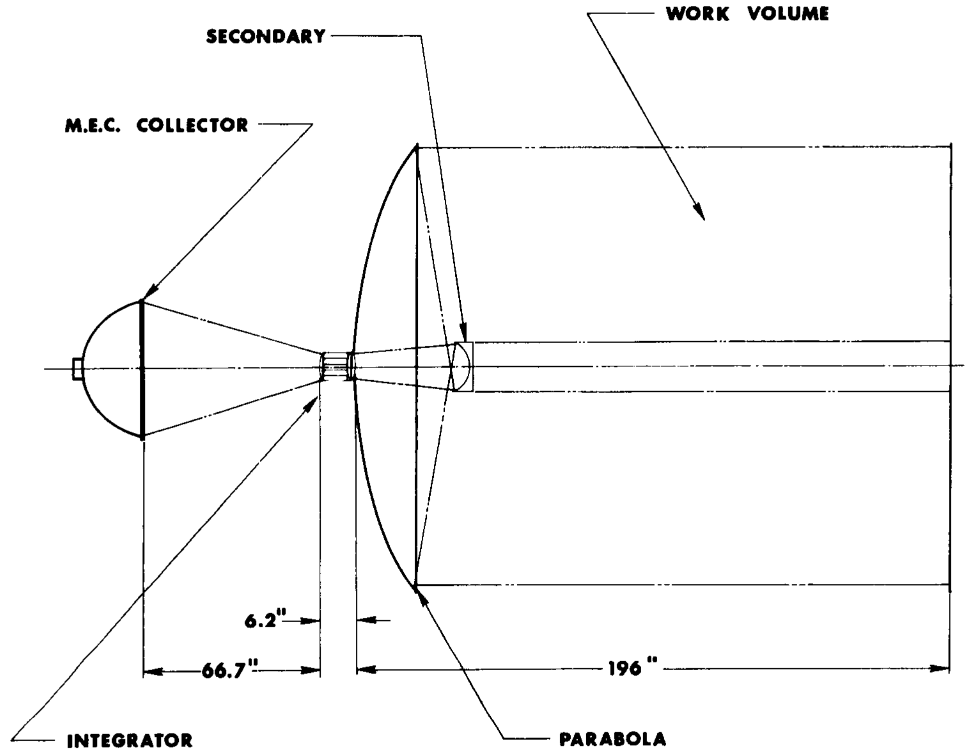

Figure 1 Optical Diagram

mator.

A spectral filter is located at the input side of the optical integrator. Its function is to remove some of the energy in the near infrared portion of the spectrum, thereby improving the systems spectral qualities.

The refractive elements of the system are fabricated from U.V. grade fused silica.[2] The reflective surfaces are all aluminized for peak reflectivity at 300 nanometers. The collector and folding mirror are not overcoated. The collimating optics are overcoated with magnesium fluoride for peak reflectivity at 300 nanometers.

In the following sections more detailed descriptions of the components of the simulator optical system are given.

A. Lamp and Collector

The lamp is a 20 KW compact arc lamp with water cooled anode and cathode.[3] It is of the J.I.S. (Joint Industry Standard) configuration with a 12 mm cold arc gap and fused quartz envelope.[4] This type of lamp typically converts about 50 percent of its electrical input to radiant output.

The M.E.C.[c] collector is shown in Figure 2.[5] The collector is machined from an aluminum forging and plated with electroless nickel. It was then ground and polished to a high optical finish and aluminized. Cooling coils are attached as shown to remove the heat load absorbed from the lamp. The collector is water cooled in series with the xenon lamp.

B. Trichroic Spectral Filter

The spectral filter coating is deposited on a fused silica substrate. The coating generally has a high transmission value for most of solar spectral range (see Figure 3). The peak reflectance of the coating occurs in the near infrared between 800 and 900 nanometers. This type of filter is called "trichroic" since it exhibits a resonant increase in reflectivity at one third the primary rejection wavelength.

This coating design is a compromise from what would typically be used in an aerospace spectral match application. The primary wavelength was purposely shifted to shorter wavelengths so that the resonant high reflectivity band would fall entirely below 300 nanometers. Since the important photochemical reactions occurring in the polluted troposphere are initiated in the 300 to 450 nanometer region, it was felt that maintaining a good continuum of radiation in this region must take precedence over an ideal spectral match in the visible and IR regions.

The energy absorption of the coating is very small, being on the order of 0.2 to 0.4%. The energy is either very highly transmitted or reflected. It is for this reason, and the fact that the coating materials are very stable, that the filter can be inserted at such a high intensity area at the input of the

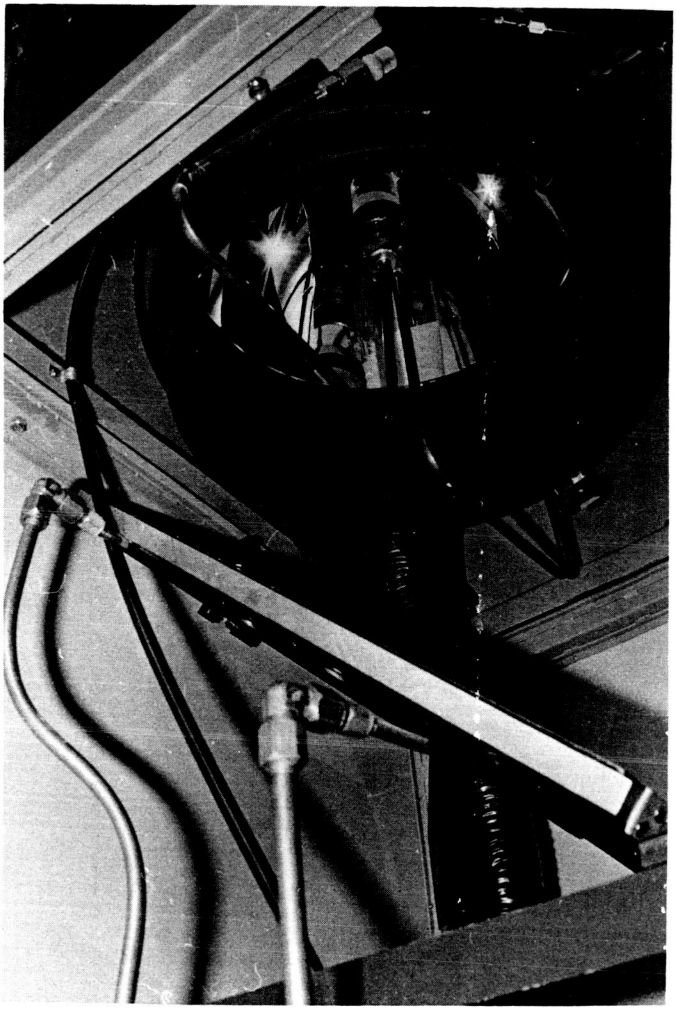

Figure 2
M.E.C. Collector and
Lampholder Assembly

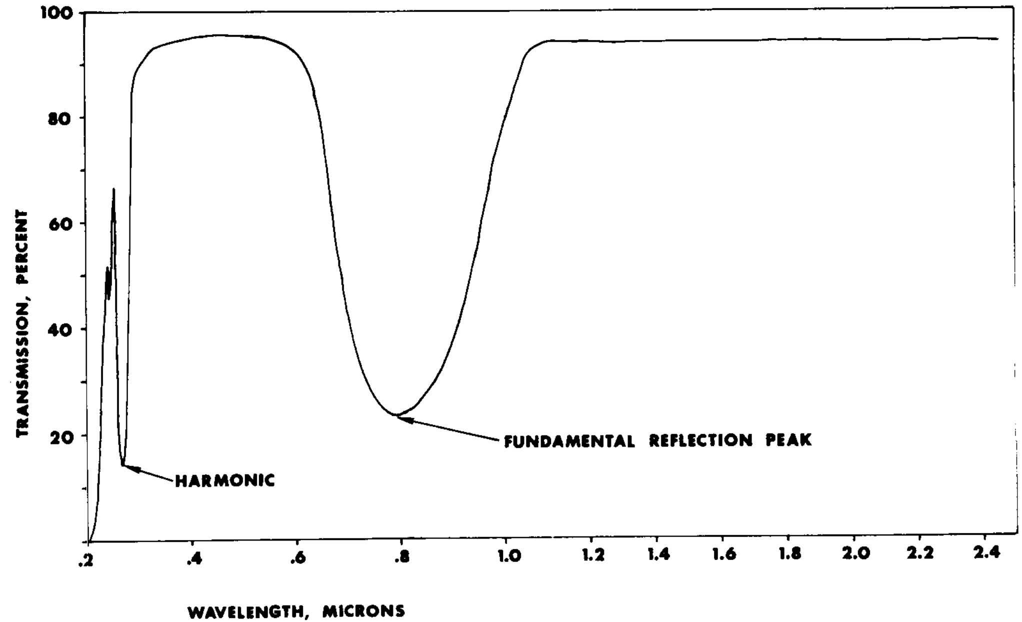

Figure 3
Transmission Curve of
Trichroic Filter

integrator.

C. Absorptive Filters

The system has the necessary bracketry and spill tray to allow for insertion of a large variety of additional absorption cells which may be required to modify the spectrum during the research programs. These include solution absorption filters (i.e. aqueous solutions of metal salts) and interference bandpass and cutoff filters.

D. Optical Integrator

The optical integrator consists of 34 round cylindrical lenses with an input and output lens. The function of the integrator is to separate the beam coming in from the collector into separate channels each of which projects onto the secondary mirror. The output lens causes the channels to superimpose at the secondary mirror. The superimposed images are re-imaged at the test plane.

There is a large intensity gradient at the input of the integrator. Each channel of the integrator relays to the test area, an image of the portion of the gradient which is incident at its input end. Since an opposing channel will have a nearly opposite gradient the two channels will approximately cancel each others intensity gradients. When this effect is summed up over all of the channels, the result is a highly uniform test area.

E. Collimating System

The modified Gregorian collimating system uses a spherical secondary mirror and a parabolic primary reflector to image the output of the integrator at infinity and place the test plane image at a distance of 162 inches from the secondary mirror.

The spherical mirror is a water-cooled, metal mirror fabricated in a manner similar to the collector.

The parabolic primary mirror is a 25.6 inch focal length searchlight mirrormade of electroformed copper approximately 3/16 inch thick. Its optical surface is rhodium plated, aluminized and overcoated with magnesium fluoride. The mirror was originally fabricated for a military searchlight. The use of this mirror and its searchlight mounting drum effected a major cost savings with only a small penalty in uniformity.

The use of an on-axis collimating system causes a dark shadow in the center of the beam due to the secondary mirror. No attempt was made to fill in the hole in the center of the beam due to its small area (~4%) relative to the overall area of the beam. The hole is 10 inches diameter at the entrance to the chamber and about 4.5 inches diameter at the chamber exit window.

IV. MECHANICAL DESIGN

The mechanical construction of the 20 KW solar simulator is shown in Figure 4. The housing structure is welded from square steel structural tubing. The water cooling system including the reservoir, pump and heat exchanger are all inside the lamphouse. The system has a kinematically designed lampholder assembly to allow precise adjustments for optical alignment. The system has a water-cooled, manually-operated douser and an air cooling system which draws its air supply through a filter from the laboratory area. The air is used to cool the lamp and provide a mass air flow through the system. The lamphouse exhausts through a duct to the outside of the laboratory at approximately 400 CFM. The area between the collimator drum and the evacuable chamber is sealed off from the laboratory by a flexible shroud. There is a blower which circulates air through the collimation unit. Its exhaust is into the simulator air intake.

The system is equipped with jacks for leveling and castors for mobility. The nominal working beam height is 48 inches from the floor to the centerline of the beam. The system is self-contained except for the power supplies which are mounted remotely.

V. ELECTRICAL DESIGN

All of the operating controls are located on the control and diagnostic panels which in turn are located on the lamphouse. The panel for facilities hookup of water and power is located on the side opposite the control panel. The diagnostic panel displays the condition of the safety interlocks each of which has the ability to shut down the system if a fault occurs. The interlocked functions are: lamp cooling water flow; facility water flow; douser water flow; lamp air flow; and lamphouse doors.

In addition there is a non-displayed interlock in the power supplies to protect them from excessively high temperatures due to overload.

The control circuit and all power mains are fused for protection.

There are two 15 KW power supplies operated in parallel from a single set of duplex controls on the control panel.[6] The power supplies are equipped with current ripple filters to limit the RMS current ripple to 2% maximum. The power supplies share the load equally at all times and have a continuous power rating of 30 KW at any current level up to 700 amps.

The power supplies are equipped with special weather shields and are placed outdoors to conserve laboratory space.

The interconnecting cables to the lamphouse are 65 feet long. The power supply open circuit voltage is approximately 100 VDC to facilitate easy starting of the lamp. The power supplies operate from a power-factor corrected source of 208 VAC, 3 phase, 60 Hz.

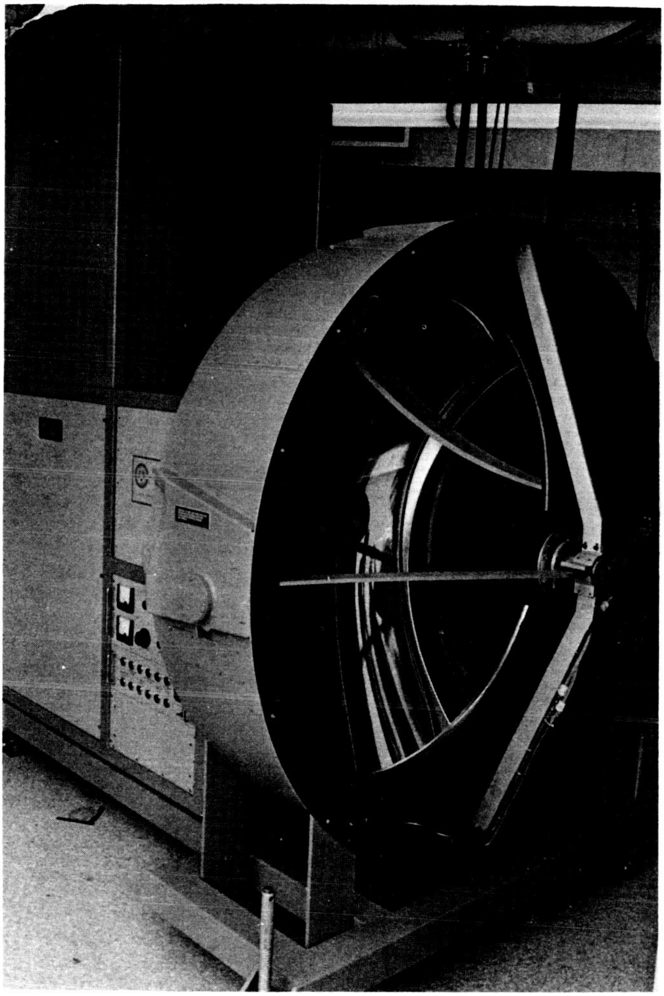

Figure 4
20KW Solar Simulator

The lamp ignitor is a forced-convection cooled unit with 1000 AMP current rating. The unit produces up to 50,000 volts AC to break down the arc gap and start current flowing in the lamp.

VI. OPERATIONAL SAFETY

The system has several red warning signs to alert personnel in the simulator area to the hazards of high pressure lamp explosion, ultraviolet burns and the danger of looking back into the system or at the arc without eye protection.

The ozone generated by the system is drawn out of the lamphouse by an exhaust fan which maintains the system at a negative internal pressure. The ozone is discharged outside the laboratory.

When the system bay doors are closed for operation, the lamp presents no explosion problem since the lamphouse will contain any lamp explosion. Personnel making adjustments to the system while the lamp is on are required to wear protective clothing.

When the lamp is to be removed a special tool is used to hold the lamp while its mounting screws are being removed. This tool minimizes the exposure time for the person removing the lamp. Again, protective clothing is required.

VII. PERFORMANCE

The system was performance tested after installation at the SAPRC laboratory. The following is a synopsis of those tests.

A. Total Irradiance

The intensity of the beam was measured using a radiometer with a blackened receiver for flat spectral response.[7] The irradiance intensity was measured at 4 points at a radius of 11 inches and 4 points at a radius of 16 inches. The mean value of these measurements was accepted as the intensity level. The simulator produced 1.0 solar constants[8] at a lamp input power of 16 KW. The intensity at 20 KW lamp input power was 1.32 solar constants.[8] All intensity tests were made with the removable trichroic spectral filter in place.

B. Irradiance Uniformity

The irradiance uniformity was measured with the same detector as used for measuring total irradiance of the simulator. The detector was placed at various radii from 6 inches to 23 inches. A total of 48 readings were taken and the uniformity of irradiance was determined to be ±10.4%. There is a dark hole in the center of the beam which is 4 1/2 inches diameter at the nominal test plane.

C. Solar Subtense Angle

The solar subtense angle was measured with a sextant at the nominal test plane. The solar subtense angle is ±1° 6' at a point near the beam center and ±1° 9' at a point near the edge.

D. Beam Douser

The system is equipped with a beam douser to occult the beam. The douser is water cooled and absorbs the heat load projected from the lamp and collector assembly onto the integrator. It can absorb the heat load continuously at lamp powers in excess of 20 KW.

In the photochemistry investigation for which the simulator is being employed, it is quite important to have the capacity to shutter the beam by means of the douser until complete warm-up of the system occurs. As Demerjian, Kerr and Calvert have pointed out, for conventional chambers in which it is not possible to shutter the irradiation system until full light intensity is achieved initial reaction rates will show an induction period which will be due largely to an artifact related to the lamp warm-up characteristics.[1]

E. Spectral Irradiance

The spectral irradiance of the beam was measured with a Carl Zeiss spectroradiometer.[9] The spectroradiometer has been modified for solar simulator measurements by ACC. The incident radiation is reflected from a magnesium oxide diffuser into the entrance slit of the monochromator. The diffuser is first positioned to look at the unknown source and a reading is taken. The diffuser is then rotated 90° to look at a reference source and another reading is taken. The reference source is a 1000 watt, quartz halogen lamp whose calibration is NBS traceable. The readings are then compared to determine the spectral irradiance of the unknown source.

The spectrum of the beam was measured with and without the trichroic spectral filter and the resultant measurements are as shown in Figure 5.

VIII. CONCLUSION

The solar simulator system described above is now in routine operation in the environmental chamber laboratory of the Statewide Air Pollution Research Center. It is commonly employed for six-hour irradiations of either synthetic smog mixtures or ambient Riverside air. Plans are underway to equip the simulator power control with a clock drive which will permit simulation of the diurnal variation in solar intensity in the atmosphere. This refinement would be difficult to achieve readily in chambers with conventional irradiation sources and to our knowledge has not

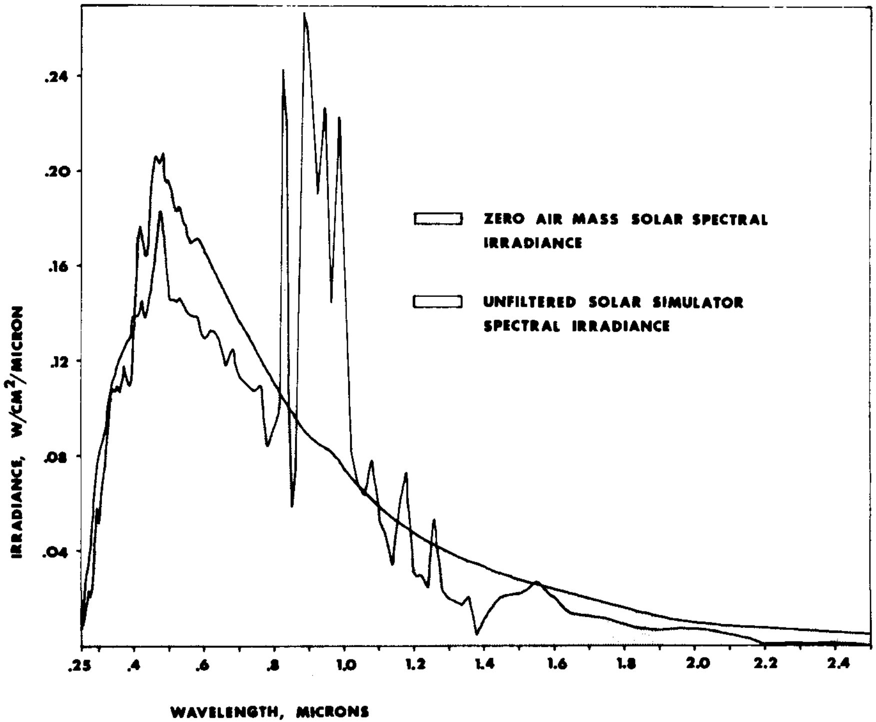

Figure 5a
Unfiltered Solar Simulator
Spectral Irradiance

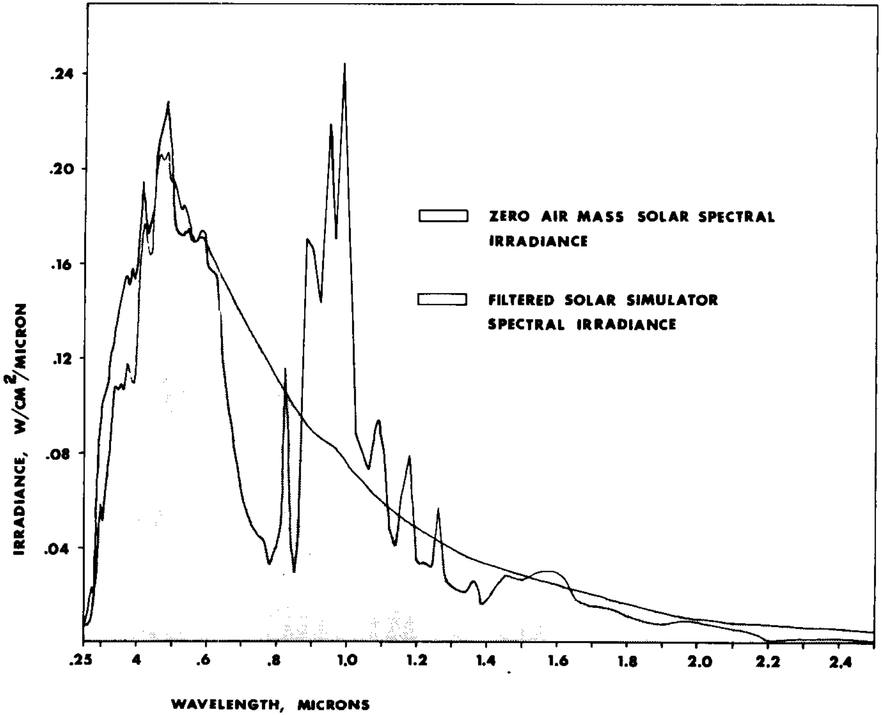

Figure 5b
Filtered Solar Simulator
Spectral Irradiance

been employed in previous smog chamber studies.

Although the primary research goal of the chamber facility is to investigate the photochemistry of the polluted troposphere, temperature and pressure control in the evacuable chamber permits simulating the earth's atmosphere to stratospheric altitudes. Since the evacuable chamber is also equipped with high-grade quartz windows, which are 90% transmitting down to wavelengths as short as 220 nanometers, good spectral and intensity simulation of photolysing radiation at upper altitudes is possible. The abundance of energy below 300 nanometers produced by the 20 KW system will permit such upper altitude studies to be conducted in the evacuable chamber.

Finally, although it is not presently anticipated that experiments will be carried out at intensities in excess of one solar constant, greater intensity can be obtained, if necessary, by use of a reflector outside the far end of the evacuable chamber which results in a two-pass configuration. The simulator can also be operated with a 25 KW xenon lamp if still greater intensity is required.

Acknowledgments

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